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Abstract: Many bays in the world are threatened by coastal hazards such as storm surge, river flood and tsunami. Since most of the existing studies have been focused on one or two of them, in this study, the assessment of coastal vulnerability caused by the three hazards was the research target. Inundation simulation is a widely used and straightforward way in coastal vulnerability assessments; however, it is computationally expensive, and considering an increase in the number of cases in multi-hazard analysis, an efficient method was proposed using an estimated overflow volume without computing inundation, which was validated by comparing with inundation simulation. It shows that when free overflow is dominant, this method is consistent with inundation simulation approach. Using Tokyo Bay as a study area, the efficient method was then applied to multi-hazard vulnerability assessment. By comparing the overflow volume maps and maximum anomaly distribution along the coasts for four types of hazards (worst storm surge; worst concurrent storm surge and river flood; worst concurrent storm surge, river flood and Tokai-Tonankai earthquake tsunami; worst concurrent storm surge, river flood and Tokyo inland earthquake tsunami), we investigated the characteristics of different types of hazards and identified the difference between single hazard and multi-hazards. The characteristic of overflow volume along the coasts is similar to that of maximum anomaly distribution, especially for only storm surge case, the multi-hazard case combining storm surge and river flood, and the multi-hazard case combining storm surge, Tokyo inland earthquake tsunami and river flood. However, for multi-hazard case combining storm surge, Tokai-Tonankai earthquake tsunami and river flood, only by the maximum anomaly distribution, it cannot reflect the real overflow volume condition. For only storm surge case and multi-hazard case combining storm surge and river flood, the head of the bay suffers the highest vulnerability while for multi-hazard cases combining storms surge, tsunami and river flood, the difference of vulnerability in the north and south of the bay is not significant. The difference of superposing method and concurrent method for computing multi-hazards was also compared. It was found that the linear superposing method tends to overestimate the total water elevation in coastal region; however, in the coasts where superposing method underestimates the multi-hazard anomalies, upgrading dikes needs to be considered by policymakers.

Keywords: Coastal vulnerability; Storm surges; Tsunamis; River floods; Overflows

1. Introduction

Tokyo Bay areas are the major political and economic center in Japan with a large population, which has, however, been exposed to several types of coastal hazards, including typhoon storm surges, river floods and earthquake tsunamis.

45 Among the historical storm surge events happened in Tokyo Bay, the typhoon in the 6th year of Taisho era (1917)
46 caused one of the largest storm surges exceeding the coastal defense system and caused extensive damage to human
47 lives and properties (Miyazaki, 2003). In recent history, Typhoon Hagibis, struck Japan on October 12th, 2019, cut
48 through the eastern part of Honshu Island, and caused serious damage including 93 people deaths and more than
49 87,000 houses damaged (NHK WORLD-JAPAN News, 2019). Typhoon Faxai passed through Tokyo Bay on
50 September 9th, 2019, caused at least 3 deaths and about 40 injured (The Japan Times, 2019). Though the major coastal
51 hazard in the head of Tokyo Bay is storm surge, tsunami also happened once a while in the bay throughout the history.
52 In the 2011 Tohoku earthquake tsunami, part of the coast in Tokyo Bay was heavily damaged including the seaweed
53 farming in Futtsu Cape and the northern part of the Banzu tidal flat, and inundation was also observed in some coastal
54 areas (Sasaki et al., 2012). In addition to storm surge and tsunami, in recent years, river flood has become one of the
55 major natural disasters that happen during the summer season in Japan. According to the Disaster Management Report
56 (Cabinet Office of Japanese Government, 2015), there is a rising trend of heavy downpours in future. Therefore, there
57 is a strong need to fortify the measures for rapid, effective prediction, evacuation and relief, in anticipation of large
58 scale flood disasters.

59 To identify the vulnerability of Tokyo Bay brought by coastal hazards, a few studies have been carried out.
60 Matsuda (2013) verified the vulnerability of Tokyo to natural disasters. They found that artificial changes of natural
61 conditions including river courses and withdrawal of ground water continue to affect natural disasters and
62 countermeasures in the Tokyo lowland. Takabatake and Shibayama (2012) investigated the risk of storm surge and
63 tsunami in Tokyo Port by using three types of numerical simulations: a storm surge simulation, a tsunami simulation
64 and an overland inundation simulation. Hirano et al. (2014) investigated the maximum possible typhoon conditions
65 according to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES)
66 A1B using an atmospheric-ocean-wave coupled model, and their study shows the sea-land interaction and river flows
67 may significantly affect the depth and increase of inland inundation extent. Besides, Tokyo Metropolitan Government
68 (2018) and Chiba Prefecture Government (2018) also made efforts for prediction of maximum inundation induced by
69 expected worst typhoon storm surge. However, all these studies were focusing on single coastal hazard, e.g., either
70 storm surge or tsunami. In the recent typhoon (No. 19) on October 12, 2019, when it was passing through the Greater
71 Tokyo area, a M_w 5.7 earthquake happened near Tokyo Bay. Though no tsunami was observed at that night, it would
72 be still meaningful to identify the multi-hazard vulnerability for better disaster mitigation management considering
73 the fact that the probability of an occurrence of Tokai or Tokai-Tonankai or Tokyo Inland earthquake has been
74 increasing with time since its last occurrence.

75 Encouraged by the accuracy and extensive application of numerical models in coastal hazard management, and
76 since joint impacts of the three hazards (storm surge, tsunami, and river flood) have not been investigated, in this
77 study, numerical assessment of inundation vulnerability caused by them was the research target. Inundation simulation
78 is a widely used and straightforward way in coastal vulnerability assessments. However, it is computationally
79 expensive, and considering an increase in the number of cases in the multiple hazard analysis, it is necessary to develop
80 an efficient method to identify overall vulnerability and to screen representative scenarios for detailed analysis. For
81 this purpose, an efficient method was proposed using an estimated overflow volume without computing inundation,
82 which was validated by comparing with inundation simulation. Using Tokyo Bay as a study area, the efficient method
83 was then applied to multi-hazard vulnerability assessment. The worst multi-hazard case and the resultant vulnerability
84 was identified. The difference between single hazard and multi-hazard vulnerabilities including moderate multiple
85 hazards and worst single hazard was also discussed.

86

Figure 1. Map of Tokyo Bay with tidal stations in green-color texts (Source for tidal stations: Japan Meteorological Agency, Bureau of Port and Harbor, Tokyo Metropolitan Government, and Japan Coast Guard, https://jdoss1.jodc.go.jp/vpage/tide_j.html; Image source: Google Earth, Data SIO, NOAA, U.S. Navy, NGA, GEBCO)

2. Multi-hazard Computation

2.1 Numerical Model

The Finite Volume Community Ocean Model (FVCOM 4.3) (Chen et al., 2003) was adopted for numerical simulation. FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, three-dimensional ocean model. The model solves momentum, continuity, temperature and salinity equations. In the present computation, the ratio of internal to external time steps is set as 10 for all applications. Initial and boundary conditions for different simulation cases were presented in Table 1. Manning roughness coefficient $n = 0.025$ was used in the model to describe the ocean bottom friction.

High resolution grid is necessary to complicated port and channel configuration. To reduce the boundary influence, a wide area was selected as the computational domain (see Figure 2). The unstructured mesh system was constructed using the Surface Water Modeling System 11.1 (Aquaveo). The coastline data from the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) was utilized for the area except Tokyo Bay which was extracted from Google Earth during the mesh generation. The mesh size varies from 50 km at the open boundary to 50 m in the inner side of Tokyo Bay, and the typical mesh resolution at the Tokai-Tonankai area (the tsunami source area) is 1 km. The numbers of the mesh nodes and triangular elements in the computational domain were 141,003 and 274,482, respectively. DEM of 5-m resolution was adopted from the Geospatial Information Authority of Japan. Bathymetry data is a combination of the ETOPO-1 Global Relief model and J-EEG500 of Japan Oceanographic Data Center (a 500 meter resolution mesh dataset). Bathymetry data of 1 arc-minute resolution provided by ETOPO was used for the whole domain except for the area around Tokyo Bay and inner Tokyo Bay area. 500-meter-resolution bathymetry data was used for the area that is around Tokyo Bay, and 50-meter resolution bathymetry data was interpolated to the whole Tokyo Bay mesh.

Table 1. Initial and boundary conditions

Simulation case	Initial conditions	Boundary conditions
Storm surge simulation	Still water	Meteorological conditions including wind and atmospheric

Tsunami simulation	Water surface displacement due to earthquake	pressure due to typhoon; BKI open boundary condition
River flood simulation	Still water	No wind; BKI open boundary condition
Multi-hazard computation (storm surge, tsunami, river flood)	Water surface displacement due to earthquake	No wind; BKI open boundary condition; river discharge Meteorological conditions including wind and atmospheric pressure due to typhoon; BKI open boundary condition; river discharge

* BKI: Blumberg and Khanta implicit condition (Blumberg and Kantha, 1985)

Figure 2. Computational mesh

2.2 Storm Surge Simulation

For storm surge simulation, the model is driven by wind and atmospheric pressure. The typhoon atmospheric pressure field is computed using Myers formula (Myers, 1957) which is given by:

$$P(r) = P_c + (P_0 - P_c)e^{-\frac{r_{\max}}{r}} \quad (1)$$

where $P(r)$ is the pressure at a radial distance r from the typhoon center, P_c (hPa) is the typhoon central pressure, P_0 (= 1013.25 hPa) is the ambient or environmental pressure, r is the distance from the computational mesh node to the typhoon center, and $r_{\max}$ (km) is the maximum wind speed radius.

Following the previous study (Liu and Sasaki, 2019), Mitsuta–Fujii model was selected to compute the wind field as presented in equation (2) and the estimated pressure by equation (1) was applied to the Mitsuta–Fujii model.

$$U_w(r) = U_{w1}(r) + U_{w2}(r),$$

$$U_{w1}(r) = C_1 \left(-\frac{fr}{2} + \sqrt{\left(\frac{fr}{2}\right)^2 + \frac{r}{\rho_a} \frac{\partial P}{\partial r}} \right), \quad (2)$$

$$U_{w2}(r) = C_2 \frac{U_{w1}(r)}{U_{w1}(r_{\max})} V_T$$

where U_w is the total wind vector, U_{w1} is the wind vector induced by the rotating component, U_{w2} is the moving component, $P(r)$ is the pressure field calculated by Myers formula, C_1 and C_2 are dimensionless coefficients

135 ranging from 0.6 to 0.75, f is the Coriolis parameter, r is the distance from the typhoon center, ρ_a is the
 136 atmospheric density, and V_T is the typhoon forward speed.

137

138 2.3 Tsunami Simulation

139 The tsunami simulation method illustrated in previous studies (Wiyono et al., 2013; Chen et al., 2014) was adopted.
 140 The tsunami initial condition was calculated using Okada model (Okada, 1985), which has nine parameters of latitude
 141 (Y_0), longitude (X_0), top depth (d_c), strike (θ), dip (δ), rake (λ), fault length (L_F), width (W_F), and net slip (U_s) as
 142 shown in Figure 3.

143

Figure 3. Seismic parameters in Okada (1985) formulation

144

145

146

147 The earthquake moment magnitude (M_w) and seismic moment (M_0) has the following relation (Hanks and
 148 Kanamori, 1979):

149

$$M_w = \frac{2}{3} \log M_0 - 10.73 \quad (3)$$

150 The length L_F (km) and the width W_F (km) of earthquake fault are determined by equations (4) and (5), respectively,
 151 for a given earthquake (Leonard, 2010; Samarasekara et al., 2017).

152

$$\log_{10} M_0 = 2.5 \log_{10} L_F + 7.96 \quad (4)$$

153

$$\log_{10} W_F = 0.667 \log_{10} L_F + 1.24 \quad (5)$$

154 The average net slip (Wells and Coppersmith, 1994; Anderson et al., 1996) is calculated by:

155

$$U_s = \frac{M_0}{\mu L_F W_F} \quad (6)$$

156 where $\mu = 3.4 \times 10^{10}$ (N/m²) is the elastic modulus of crust.

157

158 2.4 River Flood Simulation

159 In the inner side of Tokyo Bay, two major rivers (Arakawa River and Edo River) are connecting to the bay. Due to the
 160 availability, only the daily discharge data of Edo River from 1955 to 2015 were collected from Edo River Office of
 161 Ministry of Land, Infrastructure, Transport and Tourism. Figure 4 shows its annual maximum discharge (a) and return
 162 period (b). Discharge of Arakawa River was estimated using the mean discharges of Arakawa River (87.5 m³/s) and
 163 Edo River (82.3 m³/s).

164 For Arakawa River, Nakagawa River, and Edo River, the flow discharge is given as 2,800 m³/s, 1,000 m³/s,
 165 and 2,600 m³/s, respectively, which is about 50-year return period discharge according to the Figure 4(b).

166

Figure 4. (a) Annual maximum discharge and (b) return period for Edo River

2.5 Land Overflow Volume

Flood map generated using inundation computation is a common and straightforward way to measure coastal vulnerability. However, it is computationally expensive considering an increase in the number of cases in multi-hazard assessment. Thus, an efficient approach using overflow volume to measure coastal vulnerability was introduced.

Figure 5 shows dike overflow process. Between section I-I and section II-II, the Bernoulli's equation could be constructed as:

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g H_1 = P_2 + \frac{1}{2}\rho v_c^2 + \rho g (H_2 + h_c) \quad (7)$$

where, P_1 and P_2 are the atmospheric pressures (hPa); ρ is the water density (kg/m^3); g is the gravitational acceleration (m/s^2); v_1 is the vertically averaged horizontal velocity in section I-I (m/s); H_1 is the water surface elevation at section I-I (m); v_c is the overflow velocity in section II-II (m/s); H_2 is the elevation of sea dike or river bank (m); h_c is the overflow depth above the sea dike or river bank (m). Rearranging equation (7) and combining the critical flow condition, the overflow depth and overflow velocity in section II-II could be yielded:

$$h_c = \frac{2}{3}(H_1 - H_2) \quad (8)$$

$$v_c = \sqrt{g \left(\frac{2}{3}(H_1 - H_2) \right)} \quad (9)$$

$$V_{\text{nodal}} = \sum_{i=1}^{N_{\text{out}}} (h_c^i v_c^i) \Delta t_{\text{out}} \quad (10)$$

To measure the vulnerability, overflow volume is calculated by:

$$V_{\text{dike}} = \sum_{j=1}^{m_c} V_{\text{nodal}_j} = \sum_{j=1}^{m_c} \left(\sum_{i=1}^{N_{\text{out}}} (h_{c_j}^i v_{c_j}^i) \Delta t_{\text{out}} \right) \quad (11)$$

where V_{dike} (m^3) is the total overflow volume of the coastline; j is the node number of the coastline; m_c is the total number of the coastline nodes. If $H_2 > H_1$, there is no overflow at the node and V_{nodal} equals 0.

Figure 5. Parameters in dike overflow process

2.6 Estimation of Overflow without Inundation Computation

2.6.1 Numerical Experiment Setup

Overflow estimation was conducted using only propagation method. To validate this method, overflow volume estimated by propagation method was compared with inundation computation. The computational meshes for only propagation method and inundation computation are shown in Figure 6. A uniform inflow was given at the left-side boundary. The computational domain for inundation computation (see Figure 6) was divided into two parts: the propagation area and inundation area. When an experiment starts, water firstly enters and propagates in the propagation area. With an increase in water level at a certain moment, water starts to overflow the coastal dike (red dash line). After that, the inundation depth in the inundation area grows gradually. Finally, the inundation depth exceeds the dike height. In this process, the estimated dike overflow volume is compared with the inundation volume in the inundation area. As dike height determines the time when overflow happens (inflow is constant), a series of dike height values are set. The dike height value varies from 0.5 m to 1.5 m with an interval of 0.5 m.

(a)

(b)

Figure 6. Mesh grid for (a) estimation of overflow volume using only propagation method and (b) inundation

computation (Uniform inflow of $2 \text{ m}^3/\text{s}$ per unit length is given at the left-side boundary; P_1 , P_2 , P_3 and P_4 are assumed as 4 observation floats, they can only move vertically with the water level change at its location, P_1 is on the dike, the distance of P_2 to dike, P_3 to dike, and P_3 to P_4 is 10 m, 5 m, and 10 m, respectively) and bathymetry configuration for dike height 0.5 m

2.6.2 Verification

In Figure 7, comparisons of the estimated dike overflow volumes and inundation volumes are shown in the left panels while time series of water elevations at four observation points are shown in the right panels, for cases with dike heights of (a) 0.5 m, (b) 1.0 m, and (c) 1.5 m, respectively.

Figure 7. Comparisons of estimated overflow volumes and inundation volumes (left panel), and time-series water elevations change at four observation points (right panel) for cases with dike heights of (a) 0.5 m, (b) 1.0 m, and (c) 1.5 m (short pink line in the vertical axis shows the crown height).

232

233 With a change in dike height, the consistency between estimated dike overflow volume and inundation volume
 234 also varied. For instance, in the case with dike height of 1.5 m (see the left panel of Figure 7(c)), from around 900 s
 235 to 1250 s, estimated dike overflow volume was consistent with the inundation volume while after 1250 s, a large
 236 discrepancy between them was observed. In Figure 7(a) and (b), the consistent period was from 280 s to 600 s and
 237 from 600 s to 1100 s, respectively. This phenomenon could be explained from the time-series water elevation at four
 238 observation points (P_1 , P_2 , P_3 and P_4). In the right panel of Figure 7(c), the elevation of three observation points (P_1 ,
 239 P_3 and P_4) did not change from 0 s to around 900 s, being always equal to the elevation of bathymetry, e.g., green
 240 color line (P_1) was 1.5 m corresponding to the dike height; blue color line (P_3) was 0.2 m corresponding to the
 241 bathymetry in the inundation area. This was because during this period, the water only propagated in the propagation
 242 area, and it did not reach the dike crown. However, the situation of P_2 was different, it started from 0 m, and just
 243 after a short time period (about 80 s), the elevation of P_2 (yellow color line) began to grow, which was due to the
 244 reason that the inflow needed short time to reach P_2 from the left boundary. When time was 900 s, P_2 reached the
 245 dike crown height, and P_3 and P_4 started to rise. At time = 1250 s, P_3 and P_4 reached the same elevation as other
 246 two points, and the overflow became completely submerged type. From this moment, the overflow volume was not
 247 consistent with the inundation volume.

248 Therefore, this approach can be used for free overflow conditions. In the present study, we assume that the
 249 inundation depth would not exceed the summation of dike height and overflow depth, which means free overflow
 250 type is dominant.

251

252 2.7 Multi-hazard Scenarios

253 Tokyo Metropolitan Government (2018) and Chiba Prefecture Government (2018) conducted numerical assessment
 254 for worst storm surge cases in Tokyo Bay. Four typical typhoon courses were created, which originated from serious
 255 historical typhoons passing through the eastern coast of Japan. They are Typhoon Tip happened in 1979, Taisho 6th
 256 year (1917) Typhoon, Ise Bay Typhoon (Typhoon Vera in 1959), and Typhoon Kitty in 1949. To investigate the worst
 257 condition of storm surge, each typhoon course has several assumed parallel tracks with the same intensity, as shown
 258 in Figure 8.

259

260

261

262

Figure 8. Modeled typhoon tracks

263 The intensity of assumed typhoon cases was fixed. The central pressure was 910 hPa, the radius of maximum
 264 wind was 75 km, and the forward translational wind speed was 30 m/s. According to the JMA best track data archive,
 265 the selected typhoon intensity was around 1,000~5,000 years return period. From Table 2, the maximum storm surge
 266 anomaly in the inner side of Tokyo Bay was larger than that in the southern part of the bay. In the multi-hazard

267 assessment section, typhoon tracks T1S2, T2S3, T3S3, T4S1 and T4S2 were selected as the scenario components
 268 because these five cases generated the largest anomalies in the northern part of the bay.

269

270 Table 2. Maximum storm surge anomalies (m) at stations in Tokyo Bay for the modeled typhoon courses

Course name	Kurihama	Yokosuka	Yokohama	Kawasaki	Shibaura	Tokyo Harumi	Chiba
T1	1.02	0.90	1.07	1.24	1.34	1.38	1.98
T2	1.05	0.87	1.07	1.20	1.37	1.43	2.04
T3	1.03	0.96	1.25	1.24	1.43	1.54	1.89
T4	0.96	1.01	1.29	1.35	1.58	1.71	1.86

271

272 Currently, tsunami induced by a Tokai-Tonankai-Nankai type earthquake and a potential inland earthquake that
 273 may happen near Tokyo metropolitan area has been a major concern in Tokyo Bay (Sasaki et al., 2012). Particularly,
 274 there is a high possibility that a Tokai-Tonankai type earthquake would happen in the near future due to its short return
 275 period of around 120 years. To cover the earthquake cases as much as possible, the earthquake fault area was calculated
 276 using a combination of the fixed rupture length and width of 50 km $\times$ 25 km rectangular sub-faults; thus Zone 1 (the
 277 potential maximum fault area of Tokai-Tonankai type earthquake using red color mesh) and Zone 2 (the potential
 278 maximum fault area of Tokyo inland type earthquake using blue color mesh) were divided by a number of 50 km $\times$
 279 25 km cells, as shown in Figure 9(a).

280

281

282

(a)

(b)

283 Figure 9. (a): Potential maximum fault areas for Tokai-Tonankai type earthquake (red color), and Tokyo inland type
 284 earthquake (blue color); (b): Fault areas for a M_w 8.0 earthquake in Zone 1 (N_{LF} and N_{WF} are the total numbers of
 285 the meshes covering the length and width of the potential maximum fault area, N_L and N_W are the total numbers
 286 of sub-faults covering the length L_F and width W_F for a specific earthquake fault. Green color rectangle covering
 287 four mesh cells in length and two mesh cells in width represents one possible sub-fault for a M_w 8.0 earthquake,
 288 and by shifting the green color rectangle every time one mesh cell, from green color rectangle to yellow color
 289 rectangle, and then from yellow color rectangle to blue color rectangle, etc. Then, all possible sub-faults can be
 290 obtained.)

291

292 The calculated L_F and W_F using equations (4) and (5) were rounded off to be multiples of 50 km and 25 km,
 293 respectively (e.g., Samarasekara et al., 2017). Figure 9(b) shows an example of how fault areas were built for a M_w
 294 8.0 earthquake. The total number N of possible rectangular tsunami faults for a given earthquake M_w in Zone 1 was
 295 estimated by:

296

$$N = (N_{LF} + 1 - N_L) \times (N_{WF} + 1 - N_W) \quad (12)$$

297

$$N_{LF} = 8, N_{WF} = 8 \quad (13)$$

$$N_L \approx \frac{L}{50}, N_W \approx \frac{W}{25} \quad (14)$$

For a M_w 8.0 earthquake, the fault rupture length and width were:

$$L_F = 179.47 \text{ km}, W_F = 55.29 \text{ km} \quad (15)$$

$$N_L \approx 4, N_W \approx 2 \quad (16)$$

$$N = (8 + 1 - 4) \times (8 + 1 - 2) = 35 \quad (17)$$

According to the Disaster Management Report (Cabinet Office of Japanese Government, 2015), probability of a large, M_w 8- M_w 9 class earthquake occurring within 30 years in Nankai Trough and a M_w 7 class earthquake occurring in the southern Kanto area within 30 years is approximately 70%, and by reviewing the historical earthquake records, several major earthquake tsunamis have hit Tokyo Bay including the 1703 Genroku Kanto earthquake (M_w 8.2) tsunami, the 1854 Ansei Tokai earthquake (M_w 8.4) tsunami, the 1923 Taisho Kanto earthquake (M_w 7.9) tsunami, the 1960 Chilean earthquake tsunami, and the 2011 Tohoku earthquake tsunami (Sasaki et al., 2012), the magnitude of devastating tsunamigenic earthquakes in Tokai-Tonankai area and Tokyo Bay was around 8.4 and 8.0, respectively. Therefore, M_w 8.4 earthquake and M_w 8.0 earthquake were selected as the scenarios for Zone 1 and Zone 2, respectively.. The number of possible tsunami fault scenarios for each of the earthquake magnitudes determined by equation (12) is summarized in Table 3.

Table 3. Number of possible tsunami fault scenarios (N) for the selected earthquake M_w

Zone 1		Zone 2	
(Tokai-Tonankai type)		(Tokyo inland type)	
M_w	Number of scenarios (N)	M_w	Number of scenarios (N)
8.4	18	8.0	3

The actual earthquake slips may not be uniform throughout the fault area, but in order to simplify the preparation procedure in the present work, a uniform slip throughout the entire rupture area was assumed. Thus, the main parameter to be modified was the magnitude of the earthquake. For tsunamigenic earthquakes happened in Zone 1, the fault parameters of Keicho earthquake are selected in Table 4, and for Zone 2, the fault parameters of Tokyo inland earthquake were used according to the materials provided by Tokyo Metropolitan Government Disaster Mitigation Report (2012). The value of longitude, latitude, fault length, fault width, and slip extent were determined by the earthquake moment magnitude and the scenarios.

Table 4. Fault parameters of tsunamigenic earthquakes in Zone 1 and Zone 2

Earthquake type	Depth (km)	Strike (°)	Dip (°)	Rake (°)
Zone 1	1	250	60	270
Zone 2	1	296	23	138

Considering the effect of time when tsunami happens during the typhoon movement, the multi-hazard scenarios were divided into two groups: Group 1 and Group 2 (see Table 5). Group 1 (1-T1S2-14 to 1-T4S2-20) contains the tsunami scenarios in Zone 1. Group 2 (2-T1S2-20 to 2-T4S2-20) contains the tsunami scenarios in Zone 2. Since in Group 1, the fault area is far from Tokyo Bay, tsunamis are considered to happen when typhoon center moves at different locations during its approaching to Tokyo Bay. In contrast, for Group 2, we only considered the situation that tsunami happens when typhoon center was located in Tokyo Bay because under this situation, the multi-hazard anomaly was the largest. Figure 10 shows the typhoon cases and initial condition of M_w 8.4 earthquake tsunami in

335 Zone 1, and M_w 8.0 earthquake tsunami in Zone 2. The detailed information of all combinations and the typhoon
336 center locations when earthquake happens could be found in Table 5.

337

338

339

340

341

342 Figure 10. (a): Typhoon cases in multi-hazard scenarios and the integers from 10 to 20 represents the typhoon
343 moving steps; (b): M_w 8.4 earthquake tsunami in Zone 1 (left panel), and M_w 8.0 earthquake tsunami in Zone 2
344 (right panel)

345

346

347 Table 5. Multi-hazard scenarios
348 (The numbers in the 4th column which could be seen in Figure 10(a) show the typhoon locations when tsunami happens)

Scenario name	Tsunami case	Typhoon case	Typhoon center location when the earthquake initiates
1-T1S2-14	M_w 8.4 earthquake in Zone 1	T1S2	14
1-T2S3-14		T2S3	
1-T3S3-14		T3S3	
1-T4S1-14		T4S1	
1-T4S2-14		T4S2	
1-T1S2-15	M_w 8.4 earthquake in Zone 1	T1S2	15
1-T2S3-15		T2S3	
1-T3S3-15		T3S3	
1-T4S1-15		T4S1	

1-T4S2-15		T4S2	
1-T1S2-16		T1S2	
1-T2S3-16	M_w 8.4 earthquake in Zone 1	T2S3	
1-T3S3-16		T3S3	16
1-T4S1-16		T4S1	
1-T4S2-16		T4S2	
1-T1S2-17		T1S2	
1-T2S3-17	M_w 8.4 earthquake in Zone 1	T2S3	
1-T3S3-17		T3S3	17
1-T4S1-17		T4S1	
1-T4S2-17		T4S2	
1-T1S2-18		T1S2	
1-T2S3-18	M_w 8.4 earthquake in Zone 1	T2S3	
1-T3S3-18		T3S3	18
1-T4S1-18		T4S1	
1-T4S2-18		T4S2	
1-T1S2-19		T1S2	
1-T2S3-19	M_w 8.4 earthquake in Zone 1	T2S3	
1-T3S3-19		T3S3	19
1-T4S1-19		T4S1	
1-T4S2-19		T4S2	
1-T1S2-20		T1S2	
1-T2S3-20	M_w 8.4 earthquake in Zone 1	T2S3	
1-T3S3-20		T3S3	20
1-T4S1-20		T4S1	
1-T4S2-20		T4S2	
2-T1S2-20		T1S2	
2-T2S3-20	M_w 8.0 earthquake in Zone 2	T2S3	
2-T3S3-20		T3S3	20
2-T4S1-20		T4S1	
2-T4S2-20		T4S2	

349

350 3. Results and Discussion

351 3.1 Multi-hazard Vulnerability

352 The concept of vulnerability is originally defined as the susceptibility to damage or injury by the United Nations
353 Disaster Relief Organization (1979). However, over the years, it has been widely recognized as the degree of
354 susceptibility or fragility of communities, systems, or groups to risks, which may also include their own capacity to
355 adapt to the hazardous conditions.

356 Vulnerability assessment is used to analyze the elements of exposure, susceptibility and resilience of any system
357 to hazard (Balci et al., 2012). However, measuring vulnerability is difficult especially in quantitative hazard studies,
358 and it is often largely dependent on the selection of indicators according to the data. In addition, current vulnerability
359 assessment studies would usually not take into account all the possible pressures that are related to the diminished
360 capacity and decreased resilience of the communities (David et al., 2000).

By referring to coastal vulnerability studies (Mani Murali et al., 2013; Benchekroun et al., 2015), most works address the problem of tsunami vulnerability using empirical fragility functions and damage curves. Tsunami fragility is defined as the structural damage probability or fatality ratio with regard to the hydrodynamic features of tsunami inundation flow, such as inundation depth, current velocity, and hydrodynamic force. Tsunami fragility curves developed using satellite remote sensing and numerical modeling represent the overall damage in the area under many types of tsunami features (inundation depth, current velocity, and hydrodynamic force) (Suppasri et al., 2012). In this study, we measure the multi-hazard vulnerability combining overflow volume and maximum anomaly distribution, and four types of hazard scenarios were prepared for the vulnerability assessment (see Table 6). Figure 11 shows the spatial variations in sea surface elevation for the worst case of storm surge, river flood and Tokai-Tonankai earthquake tsunami. To better show the similarity and difference of the four types of hazard scenarios, the maximum anomaly distributions and overflow maps of four types of hazards were shown together in Figure 12, and overflow volume was categorized into three levels as described in Table 7.

As shown in Figure 12, for Type 1 hazard (only storm surge), a few Level III coastlines were found in Arakawa River; Nakagawa River, and the mouth of Edo River (see Figure 12(a)). Except Sumidagawa River, Edo River, and Koto Ward, coast in Funabashi and Chiba coast also had overflows. After combining river flood, the range of overflow coastlines (see Figure 12(b)) in Arakawa River, Nakagawa River and Edo River expanded, while other vulnerable places in Koto Ward, Funabashi, Chiba, and Yokohama did not change much. After adding tsunami, the vulnerable coastlines further increased significantly. In Type 3 hazard combining Tokai-Tonankai tsunami, the overflow extent including the overflow coastline grew largely compared to other types of hazards (see Figure 12(c)), and Level III coastlines appeared in Sumidagawa River, Arakawa River, Nakagawa River, Edo River, Chiba coast, and reclaimed land.

From Figure 12(a) and Figure 12(b), river flood would mainly increase the overflow extent in riversides. By comparison of Figure 12(b) and Figure 12(c) or Figure 12(b) and Figure 12(d), the whole bay would suffer more overflow after combining Tokai-Tonankai earthquake tsunami or Tokyo inland earthquake tsunami, and tsunami would also deteriorate the overflow extent of riverside, even in the upstream.

Comparing the maximum anomaly distribution in Figure 12(a) and Figure 12(b), river discharge mainly enlarge the anomaly in the river channels. After combining Tokai-Tonankai earthquake tsunami, more significant anomalies happen in the head of the bay. However, the multi-hazard case combining Tokyo inland earthquake tsunami did not result in such phenomenon.

Comparing the overflow volume map and the maximum anomaly distribution in each subfigure, e.g., Figure 12(a), the characteristic of overflow volume along the coasts is similar to that of maximum anomaly distribution, especially for only storm surge case in Figure 12(a), the multi-hazard case combining storm surge and river flood in Figure 12(b), and the multi-hazard case combining storm surge, Tokyo inland earthquake tsunami and river flood in Figure 12(d), because, for example, for the former two cases, both significant anomalies and overflow volume happen in the head of the bay and rivers. However, for multi-hazard case combining storm surge, Tokai-Tonankai earthquake tsunami and river flood in Figure 12(c), only by the maximum anomaly distribution, it cannot reflect the real overflow volume condition, for instance, maximum anomalies happen in the head of the bay and rivers while coasts in Yokohama also suffer large overflow volume.

399

400

Table 6. Hazard types for vulnerability assessment

Type No.	Hazard component
1	Only storm surge (21 cases)
2	Storm surge and river flood (21 cases)
3	Storm surge, tsunami (Tokai-Tonankai) and river flood (35 cases)
4	Storm surge, tsunami (Tokyo inland type) and river flood (5 cases)

401

(a)

(b)

Figure 11. Spatial variations of sea surface elevation at (a) 0 min; (b) 10 min; (c) 200 min for worst case of storm surge, river flood and Tokai-Tonankai earthquake tsunami

Table 7. Classification of overflow volume levels

Level	Overflow Volume m^3
III	$(100000, +\infty)$
II	$(50000, 100000]$
I	$(0, 50000]$

(a)

(b)

(c)

(d)

Figure 12. Overflow volume maps (blue color texts show the river names; black color texts show the names of places mentioned in the main text) and maximum anomaly distributions in Tokyo Bay for (a) worst case of storm surge, (b) worst case of storm surge and river flood, (c) worst case of storm surge, Tokai-Tonankai earthquake tsunami and river flood, and (d) worst case of storm surge, Tokyo inland earthquake tsunami and river flood

3.2 the Difference between Single Hazard and Multi-hazard Cases

431 Since the research on the concurrence of storm surge and tsunami is very rare, we will focus on discussing it in this
432 section. To understand the difference between single hazard (tsunami or storm surge) and multi-hazard cases, a
433 comparison between a multi-hazard case (hereafter concurrent case or concurrent multi-hazard case) and a case
434 (hereafter superposing case) linearly superposing each single hazard case was conducted. The anomaly difference
435 along the coast between the concurrent multi-hazard case and the superposing case is shown in Figure 13. To show
436 the difference brought by the typhoon center locations when tsunami initiated, we chose the multi-hazard cases which
437 were composed of the same typhoon. The value was obtained by subtracting the anomaly of concurrent multi-hazard
438 case from that of superposing case. It could be found that the difference varies spatially significantly and it is larger
439 in ports and river channels than in other coastal areas. In most coastal areas, the anomaly of superposing case is greater
440 than that of concurrent case, but in some places, concurrent case results in larger anomalies than superposing case.
441 Compared to concurrent computation, superposing method overestimated the total water level for most coastlines
442 especially the Chiba Port, Yokohama Port and water channels in Koto Ward, where the difference could be more than
443 0.5 m (red color). Although no studies on the interaction between storm surge and tsunami have been found, similar
444 phenomenon has been observed in many studies (e.g., Prandle and Wolf, 1978; Johns et al., 1985; Sinha et al., 2008)
445 of the tide and storm surge interaction or tides and tsunamis interaction, which all show that such a linear superposing
446 way is not strictly correct and usually tends to overestimate the total coastal sea level elevation. From the perspective
447 of security, superposing method is acceptable but in consideration of economy for the designing and construction of
448 coastal defense infrastructure, it may not be appropriate.

449

(c)

(d)

(e)

(f)

Figure 13. Anomaly difference of the concurrent multi-hazard case and superposing case, (a) to (g): Typhoon location at 14 to 20 when tsunami initiated

Compared to the studies on the tsunami-tide interaction (e.g., Lee et al., 2015; Kowalik et al., 2006), tides in the open sea do not have dramatic effects on tsunami wave propagation such that a linear superposing method can be applied for sea level variation. In concurrent cases of our study, storm surge elevates the whole water level in the bay including that of coastal areas when typhoon passing, which may weaken the tsunami wave shoaling compared to only tsunami case (starting from still water).

A comparison of the multi-hazard case (moderate storm surge and moderate tsunami) and the single hazard case (worst storm surge) is also conducted. From Figure 14, it could be found that in the worst storm surge case, anomalies are larger than those of moderate multi-hazard case (see Figure 14(d)), especially in the north of the bay, while for multi-hazard case (see Figure 14(c)), the difference of anomaly in the north and south is not significant.

(a)

(b)

(c)

(d)

Unit: m

Figure 14. Anomalies of moderate multi-hazard case and worst storm surge case (a: moderate typhoon storm surge; b: moderate earthquake tsunami; c: concurrent moderate storm surge and moderate tsunami; d: worst storm surge)

Although the moderate multi-hazard event may cause smaller damage than largest single storm surge, the damage risk of multi-hazard event and single hazard one for local coastal areas may vary due to the different spatial patterns. In Tokyo Bay, port areas such as Chiba Port, Yokohama Port, low-lying areas such as narrow channels in Koto Ward and some other coasts like those in Funabashi and the upstream areas of the investigated rivers in the northern part of the bay need policymakers' special attention because they are more vulnerable compared to other places. To prevent the inundation and reduce the loss caused by multiple hazards, upgrading the dike heights in areas where superposing method underestimates the multi-hazard anomalies also needs to be considered. Early-warning and hazard prediction system are useful tools for disaster mitigation. However, the current system in the study region may not be able to directly provide the possible flood information when multi-hazard events happen. Thus, the capability of multi-hazard computation may need to be incorporated for more accurate hazard information. For Tokyo Bay, the current dike system is able to defend against concurrent moderate multi-hazards consisting of moderate storm surge, moderate tsunami, and river flood; however, for worst concurrent multi-hazards, policymakers may need to reconsider the

490 design code or construction standard of defending system.

491

492 4. Conclusions

493 Every year, many bays in the world suffer a lot of economic damage or even losses of human lives because of coastal
494 hazards such as storm surge, river flood and tsunami. Much effort has been made by coastal researchers to identify
495 the risks brought by the coastal hazards and the mechanisms behind them. Since no studies have been focusing on
496 concurrent hazards of storm surge, river flood and tsunami but it almost happened during the recent typhoon (No. 19)
497 on October 12, 2019 in Tokyo Bay, it is necessary to investigate the vulnerability of multi-hazards considering the
498 importance of the bay area. In the present research, an efficient method was proposed using an estimated overflow
499 volume without computing inundation, which was validated by comparing with inundation simulation. It shows that
500 when free dike overflow is dominant, this method is consistent with inundation simulation approach. Using Tokyo
501 Bay as a study area, the efficient method was then applied to the multi-hazard vulnerability assessment and the multi-
502 hazard vulnerability map was generated. By comparing the vulnerable coasts under different types of hazards, it shows
503 that river flood would mainly increase the overflow extent in riversides, the whole bay would suffer more overflow
504 in case of combining storm surge, tsunami, and river flood, and it was also found that tsunami would deteriorate the
505 overflow extent of riverside, even in the upstream. The anomaly difference of superposing case and concurrent case
506 (storm surge and tsunami happen simultaneously) is basically larger in ports and river channels than in other coastal
507 areas, which demonstrated the significant interaction of storm surge and tsunami in these areas. Worst storm surge
508 would cause larger anomalies than moderate (1 m storm surge anomaly or tsunami) multiple hazards, in which the
509 return period of these two types of hazards is basically identical. However, the damage risk of multi-hazard and single
510 hazard for local coastal areas could vary due to their different spatial patterns. Superposing method may not always
511 be an appropriate way for identifying multi-hazard risks compared to concurrent computation in coastal regions
512 because it tends to overestimate the water elevation of multi-hazards in coasts.

513

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522

523 Competing Interests

524 Fei LIU , Jundong Chen and Yulong Wang declare no competing interests.

525

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